Hybrid Game-based Distribution Network and Multi-virtual Power Plant Co-optimization

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ABSTRACT

This paper proposes a hybrid game-based distribution network-multi-virtual power plant cooperative operation strategy for the different decision-making positions of distribution networks and virtual power plants. Firstly, the distribution system operator (DSO) is introduced as the leader, and the DSO aiming at maximizing its own benefits, formulates a dynamic tariff strategy to guide the virtual power plant cooperative alliance to optimize its operation; the virtual power plant cooperative alliance, as the follower, responds to the DSO's tariff strategy and formulates an autonomous optimization strategy to minimize its own operating costs. Secondly, the Nash bargaining model is used to allocate the benefits of cooperation among the multi-virtual power plant cooperative alliance according to their internal power interactions. The dichotomous method combined with ADMM is used to solve the developed model. The example shows that the hybrid distribution network-multi-virtual power plant game model can effectively enhance the benefits of the distribution network while taking into account the interests of the lower-level virtual power plants.

Keywords: virtual power plant; distribution network; cooperative game; stackelberg game;

1. INTRODUCTION

With the concept of the energy internet, virtual power plants have a broader application prospect and are receiving attention from scholars due to their ability to integrate multiple regions and types of energy using advanced measurement, communication, and control technologies[1-4]. The potential for multi-virtual power plant in the same distribution network area to form a cooperative alliance can improve the rate of renewable energy consumption through electricity interaction[5-7]. In the gradually opening electricity market, many social capitals have emerged in the electricity market. In the future, each virtual power plant and distribution network operator in the alliance will belong to different interests. So how to mobilize the electric energy interaction among virtual power plants and realize the fair distribution of benefits as well as how to carry out electric energy flow with the distribution network side to achieve win-win cooperation among multiple entities is a difficult problem that needs to be solved.

Therefore, this paper proposes a hybrid game-based distribution network and multi-virtual power plant cooperative operation strategy to address the above-mentioned situation. Firstly, a master-slave game model is established between the DSO and multi-virtual power plant. The DSO will set up a dynamic tariff strategy for each virtual power plant with the objective of maximizing its own benefits. Secondly, the cooperative alliance of virtual power plants will optimize the dispatch according to the tariff signal given by the DSO with the objective of minimizing their own operating costs, and provide feedback the power purchased and sold to the DSO. Then, the Nash bargaining solution will allocate the benefits of cooperation among virtual power plants to further reduce their operating costs Finally, the proposed solution's effectiveness is verified through an example analysis.

2. DSO - MULTI-VIRTUAL POWER PLANT COOPERATIVE ALLIANCE OPTIMIZATION MODEL

2.1 DSO Revenue Model

The DSO acts as the game leader and sets the price at which the virtual power plant buys and sells electricity in accordance with its purchase and sale plan.
(1) Objective function
DSO aims to maximize their own benefits, including the costs and benefits of purchasing and selling electricity through grid and virtual power plant alliance.

$$C^{\mathrm{dso}} = \sum_{t=1}^{24}[(I_t^{\mathrm{sell}} - I_t^{\mathrm{dso,sell}})P_t^{\mathrm{sell}} - (I_t^{\mathrm{buy}} - I_t^{\mathrm{dso,buy}})P_t^{\mathrm{buy}}] \tag{1}$$

Where the DSO revenue is C^{dso}, $I_t^{\mathrm{dso,sell}}$ and $I_t^{\mathrm{dso,buy}}$ are the purchase and sale prices of electricity from the DSO for the virtual power plant alliance, I_t^{sell} and I_t^{buy} are the purchase and sale price of electricity from the grid for DSO. P_t^{buy} and P_t^{sell} are the amounts of electricity purchased and sold from the DSO by the virtual power plant alliance.
(2) Constraints

$$\begin{cases} \sum_{t=1}^{24} I_t^{\mathrm{dso,sell}} \le 24 \cdot \overline{I_t^{\mathrm{dso,sell}}} \\ \sum_{t=1}^{24} I_t^{\mathrm{dso,buy}} \le 24 \cdot \overline{I_t^{\mathrm{dso,buy}}} \end{cases} \tag{2}$$

$$P_t^{ij} = (\theta_t^i - \theta_t^j) / x^{ij} \tag{3}$$

$$\begin{cases} P_{\min}^{ij} \le P_t^{ij} \le P_{\max}^{ij} \\ \theta_{\min}^i \le \theta_t^i \le \theta_{\max}^i \\ \theta^{ref} = 0 \end{cases} \tag{4}$$

Constraint (2) is a price constraint on electrical energy, while (3)-(4) are constraints on DC. Where P_t^{ij} represents the line *ij* trend, x^{ij} represents the reactance of the line *ij*, θ_t^i represents the voltage angle of node *i*, θ^{ref} represents the voltage angle of the reference node.

2.2 Multi-virtual Power Plant Cooperative Alliance Operating Cost model

Each virtual power plant in multi-virtual power plant cooperative alliance is a rational and independent entity that plans its operation according to its own supply and demand, and each individual forms the alliance as a whole through power trading. Therefore, the operating costs of the virtual power plants in a multi-virtual power plant cooperative alliance are modelled, which include the costs of power trading with the DSO, the compensation costs of demand response, the maintenance costs of energy storage equipment and the costs of power interaction between virtual power plants.
(1) Objective function

$$\min C^{vpp} = \sum_{i=1}^{N} C_i^{trade} + C_i^{gas} + C_i^{es} + C_i^{dr} + C_i^{p2p}$$

$$\begin{cases} C_i^{trade} = \sum_{t=1}^{24} (I_{i,t}^{dso,buy} P_{i,t}^{buy} - I_{i,t}^{dso,sell} P_{i,t}^{sell}) \\ C_i^{gas} = \sum_{t=1}^{24} \lambda_{gas} (P_{i,t}^{gt} + H_{i,t}^{gb}) \\ C_i^{es} = \sum_{t=1}^{24} \lambda_{es} (P_{i,t}^{es,dis} + P_{i,t}^{es,cha}) \\ C_{i,t}^{dr} = \sum_{t=1}^{24} (\lambda_{e,cut} P_{i,t}^{cut} + \lambda_{e,trans} P_{i,t}^{trans} + \lambda_{h,cut} H_{i,t}^{cut}) \\ C_i^{p2p} = \sum_{t=1}^{24} \sum_{j=1, j\neq i}^{N} I_t^{i-j} P_t^{i-j} \end{cases} \tag{5}$$

where: C^{vpp} represents the daily operating cost of the cooperative alliance of virtual power plants; C_i^{trade}, C_i^{gas}, C_i^{es}, $C_{i,t}^{dr}$ and C_i^{p2p} represent the transaction cost, gas purchase cost, energy storage equipment maintenance cost, compensation cost for demand response, respectively; λ_{gas} represents the gas purchase price of the VPP; λ_{es} represents the energy storage charging and discharging maintenance cost factor; $\lambda_{e,cut}$, $\lambda_{e,trans}$ and $\lambda_{h,cut}$ represent the unit prices of compensations for curtailable electrical load, transferable electrical load and curtailable thermal load, respectively; I_t^{i-j} represents the interactive tariffs for VPP*i* and VPP*j*; P_t^{i-j} represents the amount of electricity interaction between VPP*i* and VPP*j*.

(2) Constraints

$$P_{i,t}^{buy} - P_{i,t}^{sell} + P_{i,t}^{gt} + P_{i,t}^{es,dis} - P_{i,t}^{es,cha} + P_{i,t}^{wt} + P_{i,t}^{pv} + \sum_{j=1, j\neq i}^{N} P_t^{i-j} = P_{i,t}^{load} \tag{6}$$

$$H_{i,t}^{gt} + H_{i,t}^{gb} + H_{i,t}^{hp} = H_{i,t}^{load} \tag{7}$$

$$-P_{\max}^{p2p} \leq P_t^{i-j} \leq P_{\max}^{p2p} \tag{8}$$

$$P_t^{i-j} + P_t^{j-i} = 0 \tag{9}$$

$$P_{i,t}^{load} = P_{i,t}^{pre,load} - P_{i,t}^{cut} + P_{i,t}^{trans} \tag{10}$$

$$H_{i,t}^{load} = H_{i,t}^{pre,load} - H_{i,t}^{cut} \tag{11}$$

Constraints (6)-(7) are constraints for electrical and thermal power equalization; (8)-(9) are constraints for electrical energy interaction; (10)-(11) constraints for demand response. $P_{i,t}^{gt}$, $P_{i,t}^{wt}$ and $P_{i,t}^{pv}$ represent the power of gas turbine, wind turbine and photovoltaic at time *t*. $H_{i,t}^{gt}$, $H_{i,t}^{gb}$ and $H_{i,t}^{hp}$ represent the heat power of gas turbine, gas boiler and heat pump. $P_{i,t}^{load}$ and $H_{i,t}^{load}$ represents the electric and heat load. $P_{i,t}^{pre,load}$ and $H_{i,t}^{pre,load}$ virtual power plant forecasts for electrical and thermal loads. $P_{i,t}^{cut}$, $P_{i,t}^{trans}$ and $H_{i,t}^{cut}$ represent curtailable, transferable electrical load and curtailable thermal load respectively. $P_{i,t}^{es,dis}$ and $P_{i,t}^{es,cha}$ represent energy storage charging and discharging power.

3. HYBRID GAME MODELLING AND SOLVING

3.1 DSO-Multi-Virtual Power Plant Master-Slave Game Model

The master-slave game has DSO as the leader and three virtual power plants forming a cooperative alliance as followers. The optimization problem for the upper-level leader and lower-level follower can be described as a master-slave game model with DSO as the leader and *N* virtual power plants as the followers, which can be mathematically represented as:

$$G=\left\{D\bigcup S;Y^{\mathrm{dso}},X^{\mathrm{vpp}};F^{\mathrm{dso}},F^{\mathrm{vpp}}\right\} \tag{12}$$

Where *G* represents the master-slave game model, *D* for leader, i.e. DSO; *S* for follower, i.e. multi-virtual power plant collection; $D\bigcup S$ denotes a game participant ; $Y^{\mathrm{dso}}=(I_t^{\mathrm{dso.buy}},I_t^{\mathrm{dso.sell}})$ represents the DSO strategy set i.e. the price set by the DSO for the purchase and sale of electricity. X^{vpp} represents a collection of strategies for virtual power plant cooperative alliances i.e. virtual power plants buying and selling electricity from DSO ; F^{dso} represents the leader's earnings, F^{vpp} represents the cost function for the virtual power plant alliance.

3.2 Multi-Virtual Power Plant Cooperative Game Model

A cooperative game model for a multi-virtual power plant alliance is developed based on the fundamental principles of Nash bargaining theory. The specific equation is as follows:

$$\begin{cases}\max\prod_{i=1}^{N}(C_i^{vpp,0}-C_i^{vpp})\\ \text{s.t.}\quad C_i^{vpp,0}-C_i^{vpp}\geq 0\end{cases} \tag{13}$$

where C_i^{vpp} represents the cost of VPP*i* after participating in the cooperation; $C_i^{\mathrm{vpp,0}}$ represents the Nash bargaining rupture point; i.e. the operating cost of VPP*i* before participating in the Nash bargaining; *N* is the total number of virtual plants participating in the cooperative bargaining; $C_i^{\mathrm{vpp,0}}-C_i^{\mathrm{vpp}}$ represents the benefit enhancement gained by VPP*i* after participating in the cooperative bargaining.

According to Nash bargaining theory[8,9], the equations (13) problem is solved by dividing it into two sub-problems: minimizing the cost of the alliance and maximizing the benefit of electricity payment. (1) Sub-problem 1: Cost optimization of multi-virtual power plant cooperative alliances

$$\begin{cases}\min\sum_{i=1}^{N}C_i^{\mathrm{vpp}}\\ \text{s.t.}\quad C_i^{\mathrm{vpp}}=C_i^{\mathrm{trade}}+C_i^{\mathrm{gas}}+C_i^{\mathrm{es}}+C_i^{\mathrm{dr}}\end{cases} \tag{14}$$

(2) Sub-problem 2: Transaction payment for electricity

$$\begin{cases}\min-\sum_{i=1}^{N}\ln\left(C_1^{\mathrm{vpp,*}}+C_1^{\mathrm{p2p}}-C_1^{\mathrm{vpp,0}}\right)\\ \text{s.t.}\quad C_i^{\mathrm{vpp,*}}+C_i^{\mathrm{p2p}}\geq C_i^{\mathrm{vpp,0}}\end{cases} \tag{15}$$

3.3. Hybrid Game Model Solution

The hybrid game model developed in this paper is divided into two stages. The first stage is a master-slave game for the cooperative alliance between DSO and multi-virtual power plant, while the second stage is a cooperative game among multi-virtual power plant. The dichotomous method is used to solve the first stage of the master-slave game, while the ADMM algorithm is employed to solve the second stage of the multi-virtual power plant cooperative game. The solution steps are as follows:

- Initialize the number of iterations $i=0$ and $k=0$, as well as the DSO and the initial data for each virtual power plant.
- The upper-level master-slave game model DSO is constrained by the optimal power purchase and sale plans P_t^{sell} and P_t^{buy} of the lower-level multi-virtual power plant, and the optimal purchase and sale decision of DSO and the minimum operating cost of the multi-virtual power plant cooperative alliance are solved by a dichotomous method using the CPLEX solver.
- Determine whether the upper-level master-slave game model converges. If it does not meet the convergence condition, use the solved power purchase and sale plan as data for the next iteration.
- $k=k+1$, continue iteration.
- The convergence condition is satisfied, and the iteration ends by outputting the optimal power purchase and sale plan, tariff strategy, as well as power interaction strategy for the lower-level multi-virtual power plant alliance.
- Solve the upper layer problem to obtain the optimal amount of electricity traded between micro-networks. Then substitute the solution into the lower-level problem, which is solved by using the ADMM algorithm with MOSEK solver.
- Determine whether the convergence condition is satisfied. If not, use the solved optimal interaction tariff as data for the next iteration.
- $i=i+1$, continue iteration;
- The convergence condition is satisfied, the iteration ends, and the optimal tariffs between virtual plants I_t^{1-2}, I_t^{1-3} and I_t^{2-3} are output

4 Example parameters

The example uses a modified IEEE33 node distribution network, as shown in Fig.1. VPP1, VPP2 and VPP3 are connected to the distribution network nodes through contact lines. The IEEE33 node distribution system is a classic distribution network model abstracted and equivalent from actual systems, and is a typical radial network model. The distribution network interacts with the upper-level grid through node 1. The specific parameters of the distribution network are detailed in reference [10]. Figs. (2)-(4) shows the renewable energy output and load of each VPP. Table 1 shows the time-of-use tariff parameters for a day.

Table 1. Time-of-use tariff parameters

Period	purchase price / (\$/ kW·h)	sale price / (\$/ kW·h)
23:00 - the next day 07:00	0.4	0.2
7:00 - 11:00, 14:00 - 18:00	0.75	0.4
11:00 -14:00, 18:00 - 23:00	1.2	0.6

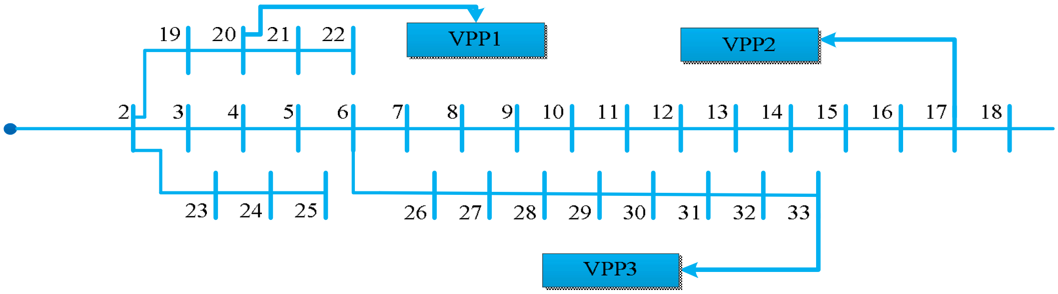

Fig. 1. IEEE33 node system topology

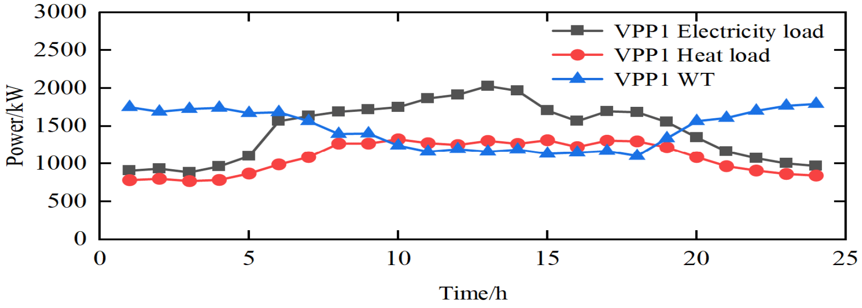

Fig. 2. VPP1 Load and WT output.

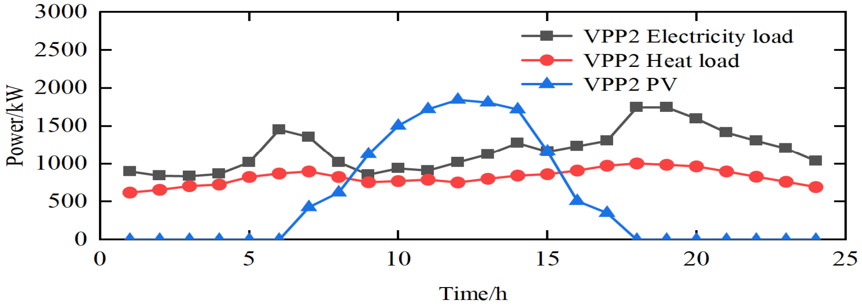

Fig. 3. VPP2 Load and PT output.

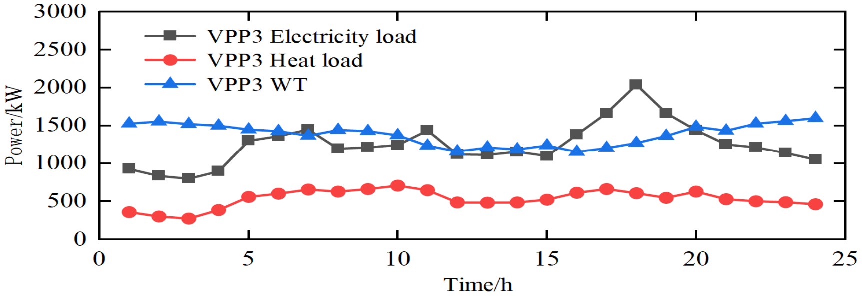

Fig. 4. VPP3 Load and WT output.

5.NUMERICAL STUDY

5.1 Strategy Analysis

To verify the effectiveness of the scheme proposed in this chapter, the following three cases were set up for comparative analysis and the results of the operations under different cases are shown in Table 2:

Case 1: Master-slave game between DSO and virtual power plant is not considered, and cooperative game between multi-virtual power plant is not considered.

Case 2: Consider the master-slave game between DSO and virtual power plants, and do not consider the cooperative game between virtual power plants.

Case 3: Consider the master-slave game between DSO and virtual power plants, and consider the cooperative game between multi-virtual power plant.

Table 2. Analysis of operating results in different cases

	DSO revenue /$	VPP	Electricity payment proceeds /$	Running costs /$	Revenue/$
Case 1	0	1	0	8632.58	0
		2	0	14226.30	0
		3	0	3463.50	0
Case 2	8317.03	1	0	8424.47	0
		2	0	14163.98	0
		3	0	3029.52	0
Case 3	7897.79	1	2104.15	8632.58	537.92
		2	3547.08	14226.30	517.81
		3	1510.49	3463.50	524.04

5.2 Analysis of trading results

In the hybrid game constructed in this paper, the master-slave game phase determines the purchase and sale prices of electricity from the DSO for the cooperative alliance of virtual power plants. The cooperative game phase sets the price of electricity for inter-virtual power plant interactions within each virtual power plant.

The power purchase from the DSO by the multi-virtual power plant consortium solved in the master-slave game phase is shown in Fig 5. The dynamic tariff strategy developed by the DSO during the master-slave game stage is shown in Fig. 6. Figs. 5 and 6 demonstrate a strong correlation between the dynamic tariffs set by the DSO and the power purchase and sale plans of the lower tier virtual power plant consortium. Specifically, during the period from 00:00 to 08:00, when the lower tier virtual power plant alliance purchases more electricity, higher tariffs are set by the DSO. During the 09:00-22:00 period, the DSO does not sell electricity to virtual power plants because its tariff is at its peak and virtual power plants prefer internal interaction to reduce operating costs. Therefore, the DSO sets a lower tariff and a higher purchase price to attract virtual power plants to sell electricity to it. During the 22:00-24:00 period, the DSO will increase both the price of electricity sold and purchased by the virtual power plant consortium in order to boost its revenue.

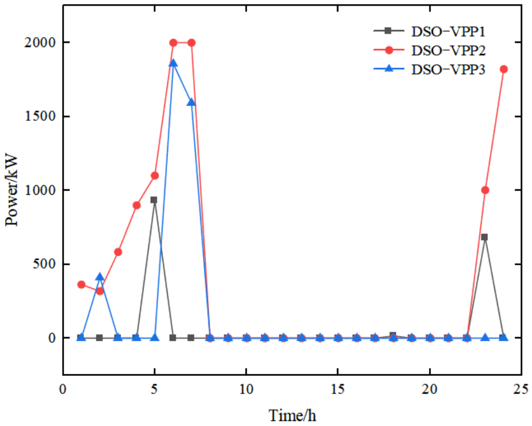

Fig. 5. Power purchase plan for lower-level virtual power plants

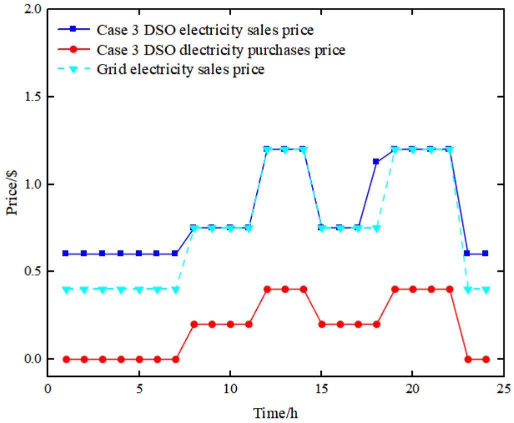

Fig. 6. Dynamic tariffs set by upper-level DSO

Figure 7 illustrates the electrical energy interactions for each virtual power plant at a lower level, while Figure 8 shows the interactive tariff for each virtual power plant at that same level.

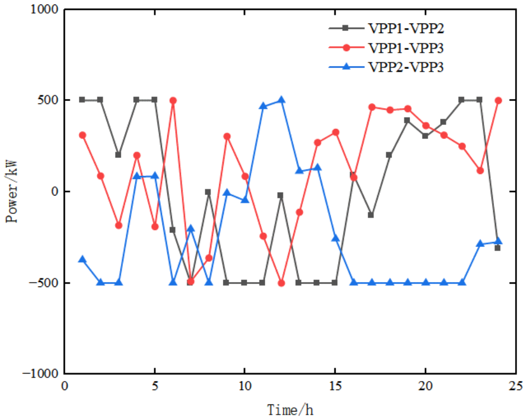

Fig.7. VPP electricity interaction results

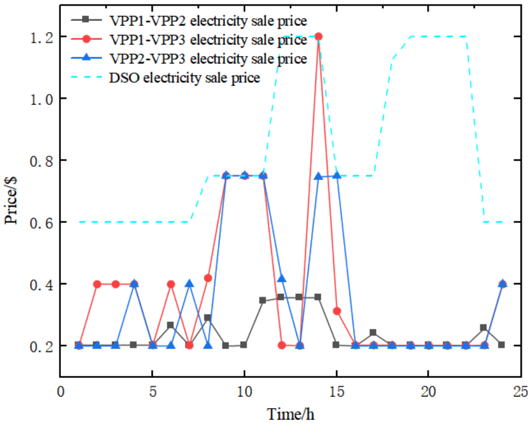

Fig.8. VPP interactive tariff

6. CONCLUSION

This paper takes the collaborative optimization operation of distribution network and multi-virtual power plant as the research object. A two-layer optimization model of the distribution network and multi-virtual power plant hybrid game is established. The DSO is the leader of the distribution network operator and the multi-virtual power plant cooperative alliance is the follower, establishing a master-slave game model. The DSO's tariff strategy is used to develop the optimal operating strategy with the objective of minimising their own operating costs. The lower layer is a cooperative game model based on the interaction between multi-virtual power plant, and Nash bargaining is used to allocate the benefits of cooperation between multi-virtual power plant. The example compares the operation cost of the hybrid game with that of the master-slave game. The results show that the model proposed in this chapter can effectively take into account the benefits of the distribution network and the multi-virtual power plant, and achieve a win-win situation for multiple entities.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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